Galactic Motions and Dynamics

Stellar Motions

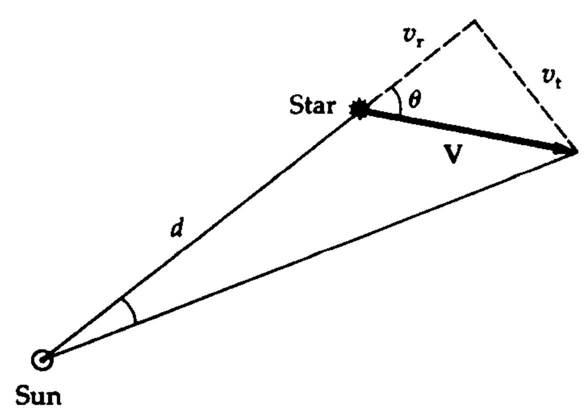
Measure Doppler shift for radial (line-of-sight) velocity,

$$v_r = \left(\frac{\Delta l}{l} \right) c.$$

Also, the <u>proper motion</u> μ (arsec/yr) in the plane of the sky to measure tangential velocity,

$$v_t = d \sin m \approx m\, d,$$

where the distance d (in pc) yields v_t in AU/year.

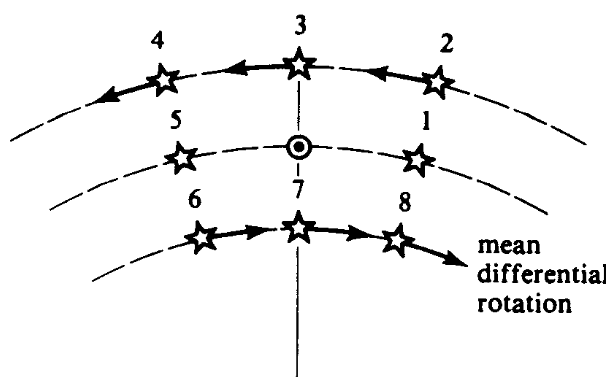


The Local Standard of Rest

Measurement of stellar motions complicated by the Sun's participation in rotation of Galactic disk.

Define a Local Standard of Rest (LSR), which follows the mean motion of disk material in the solar neighborhood.

Observations of motions *relative* to LSR (by Oort, Lindblad) reveal evidence of differential rotation in the immediate solar neighborhood. Stars interior (exterior) to Sun have higher (lower) rotation rate Ω.



The absolute motion of the LSR (not just motions relative to it) is hard to pin down.

Measuring Galactic Rotation

Current best estimates for rotational parameters of the Sun:

$$P_{Sun} = \frac{2p}{\Omega_{Sun}} = 2.4 \times 10^8 \text{ yr},$$

$$v_{Sun} = r_{Sun}\Omega_{Sun} = 220 \text{ km s}^{-1},$$

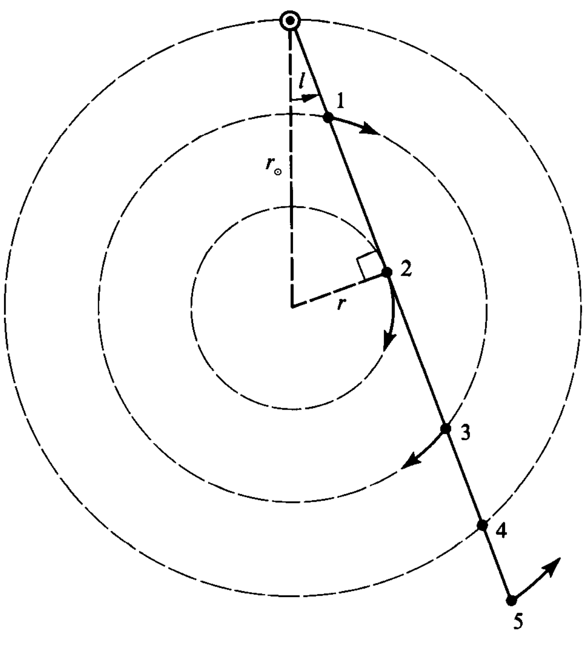
$$r_{Sun} = 8.5 \text{ kpc}.$$

Can use this to estimate the mass of the Galaxy interior to the Sun:

$$\frac{GM_G m_{Sun}}{r_{Sun}^2} = \frac{m_{Sun} v_{Sun}^2}{r_{Sun}} \quad \Rightarrow \quad M_G = \frac{r_{Sun} v_{Sun}^2}{G} \approx 1.0 \times 10^{11} M_{Sun}$$

Radio Observations of Galactic Rotation

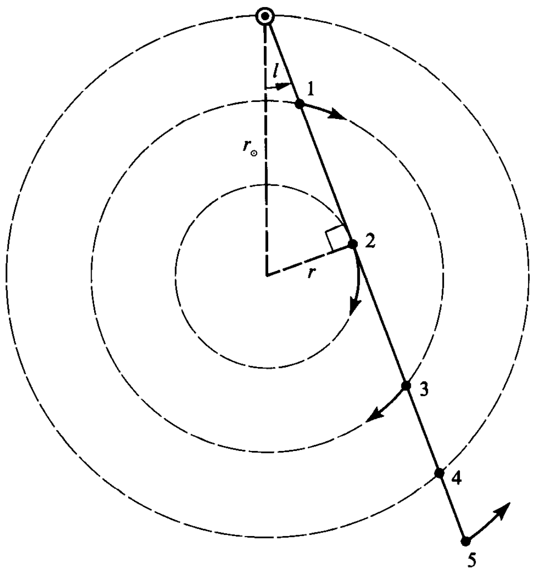
- Not limited by dust
- Use 21 cm line
- Straightforward geometric interpretation for gas interior to Sun

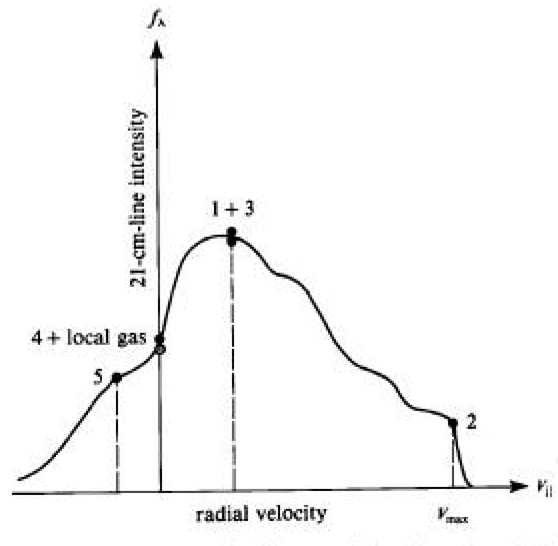


Maximum line of sight velocity relative to LSR at

$$r = r_{Sun} \sin l.$$

Radio Observations of Galactic Rotation





Apparent velocity at $r = r_{Sun} \sin l$ is

$$v_{los,\max} = r\Omega(r) - r_{Sun}\Omega_{Sun} \cos(\frac{p}{2} - l)$$

$$\Rightarrow \quad \Omega(r) = \Omega_{Sun} + \frac{v_{los,\max}}{r_{Sun} \sin l}.$$

Rotation curve is built up in this way.

Galactic Rotation - Theory

Two limits:

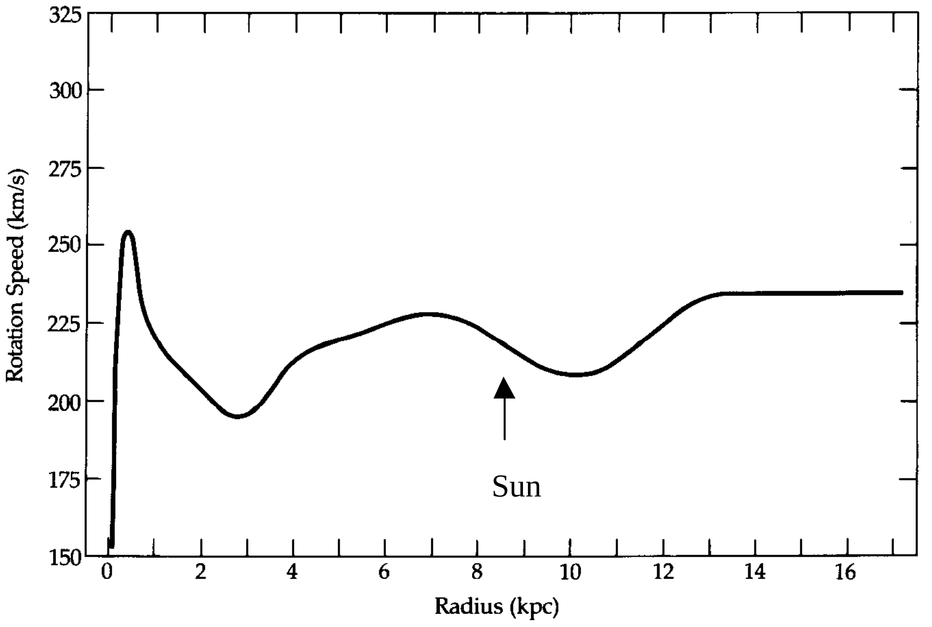
(1) within a uniform sphere, $m(r) = 4/3p\, r^3\, r$

$$\frac{v^2}{r} = \frac{Gm(r)}{r^2} \quad \Rightarrow \quad v^2 \propto \frac{m(r)}{r} \propto r^2 \quad \Rightarrow \quad v \propto r.$$ Solid-body rotation

(2) outside a point mass, $m(r) = m_0$

$$\frac{v^2}{r} = \frac{Gm_0}{r^2} \quad \Rightarrow \quad v^2 \propto \frac{m_0}{r} \propto r^{-1} \quad \Rightarrow \quad v \propto r^{-1/2}.$$ Differential rotation

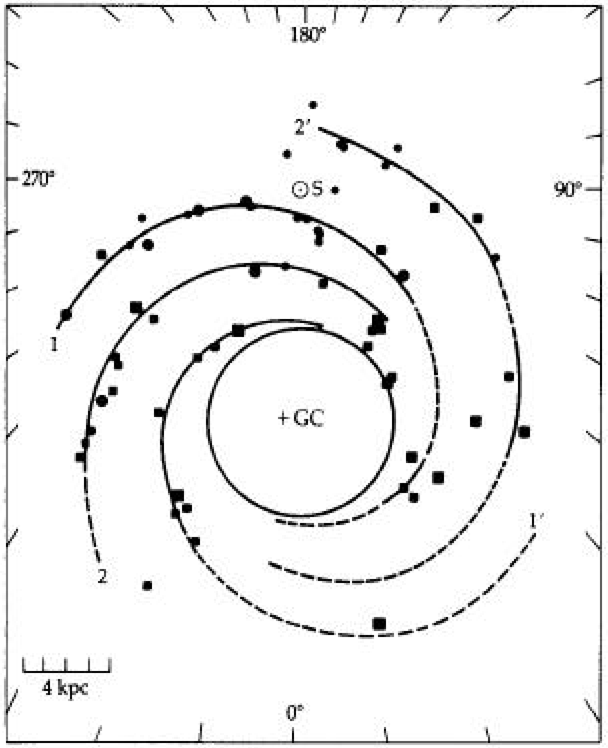
Galactic Rotation - Observations



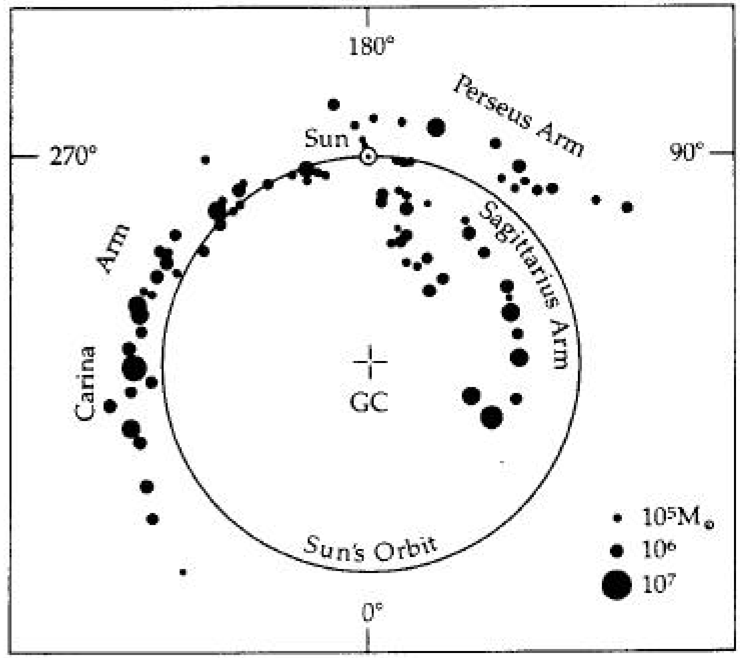
Rotation curve of our Galaxy. Note the flattening at large radii.

No Keplerian ($r^{-1/2}$) decrease of rotation velocity at large radii.
Implies at least as much mass beyond the Sun as interior to it.
This is inconsistent with observations of stars in our Galaxy.
Evidence for dark matter!

Spiral Structure



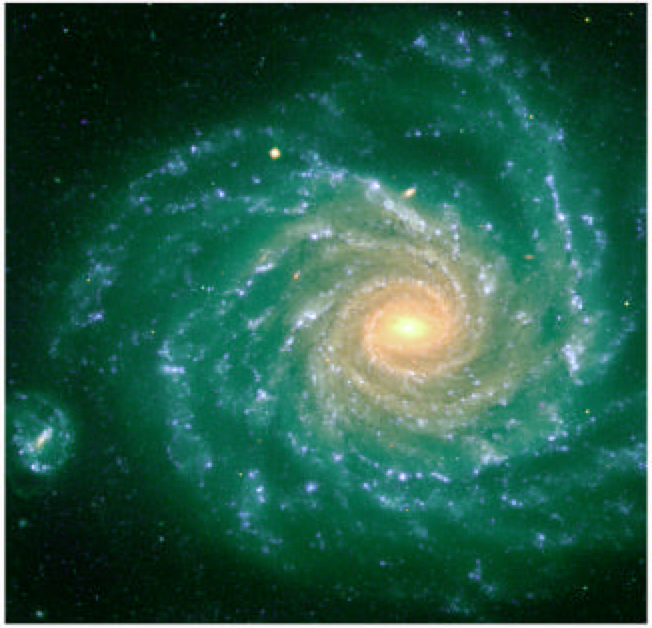
Positions of H II regions from optical observations.



Positions of Giant Molecular Clouds from radio observations.

Spiral Structure

Seen very often in external galaxies



Spiral Galaxy NGC 1232 - VLT UT 1 + FORS1

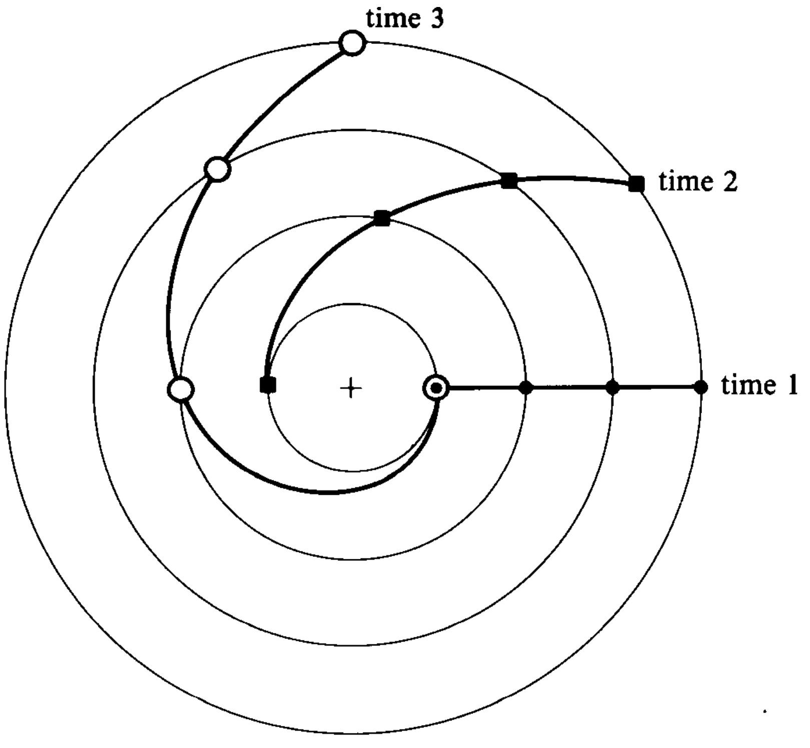
ESO PR Photo 37i/98 (25 September 1998)

Spiral Galaxy Messier 83 (VLT ANTU + FORS1)

ESO PR Photo 41/99 (29 November 1999)

Spiral Structure

Due to differential rotation?



But $P \sim 10^8$ yr in inner parts of Galaxy, while lifetime $\sim 10^{10}$ yr

=> winding dilemma!

Typically see 2-3 arms, not ~ 100.

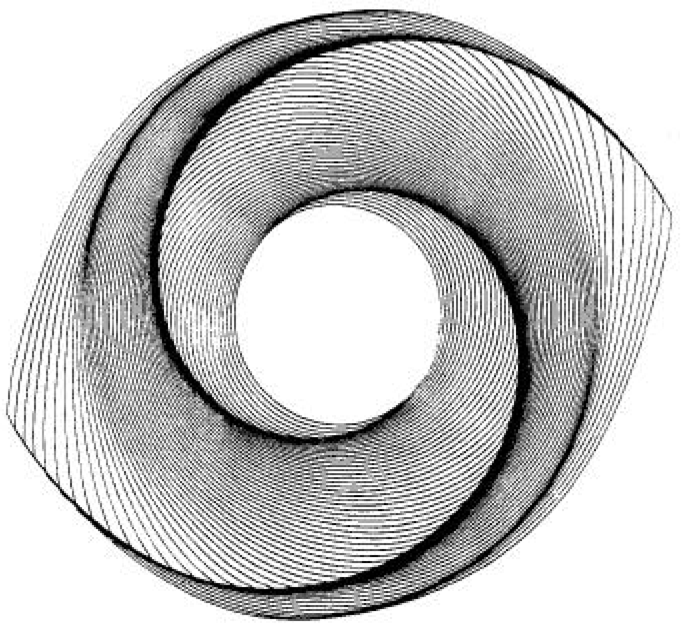
Spiral Structure

Theory: spiral density wave. Perturbations on rotating disk => non-axisymmetric structure.

• Spiral arms are like waves in water, or cars caught in a traffic jam

• Different material in arms at different times

• System reduces gravitational energy but conserves angular momentum



Streamlines of gas flow from a theoretical model of a spiral galaxy.

Spiral Structure

Model explains brightness of arms:

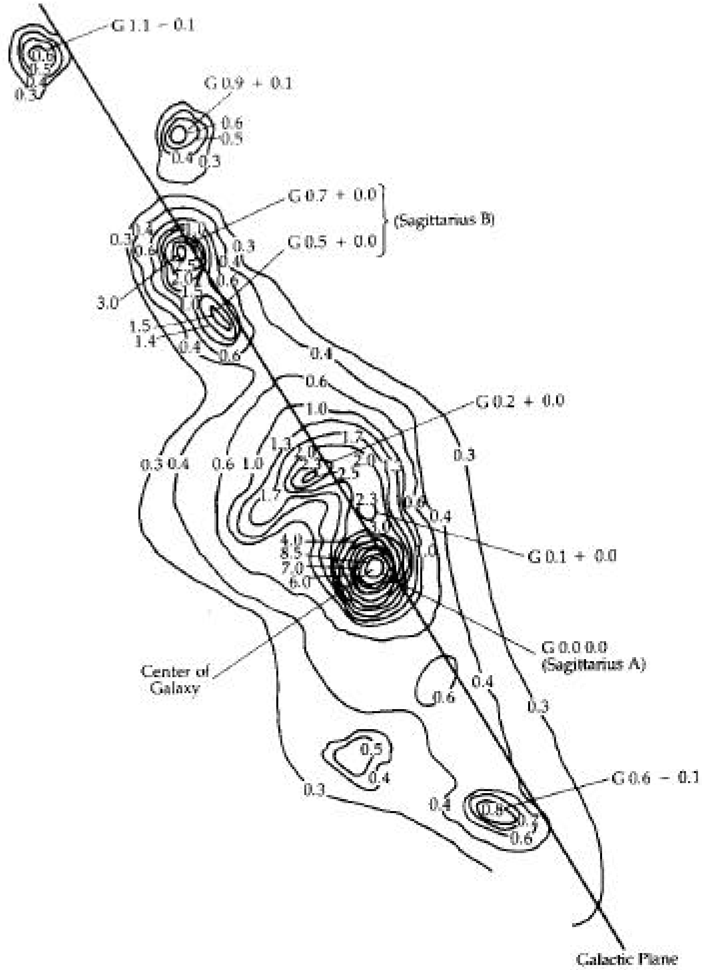
•Gas passing through arm is compressed => star formation

• Observe OB associations (very young stars) in spirals

• Arms are bright due to excess O and B stars, but star density only a few % higher than interarm region

Stellar overdensity in arms only a few %, but many more exceptionally bright (O and B) stars. Why are they not present in the interarm region?

The Galactic Center



Contours of radio emission at 3.75 cm.

Look in the radio band. Why?

Intense radio source in the direction of the center, called Sagittarius A (Sgr A). Also, X-ray and gamma ray emission.

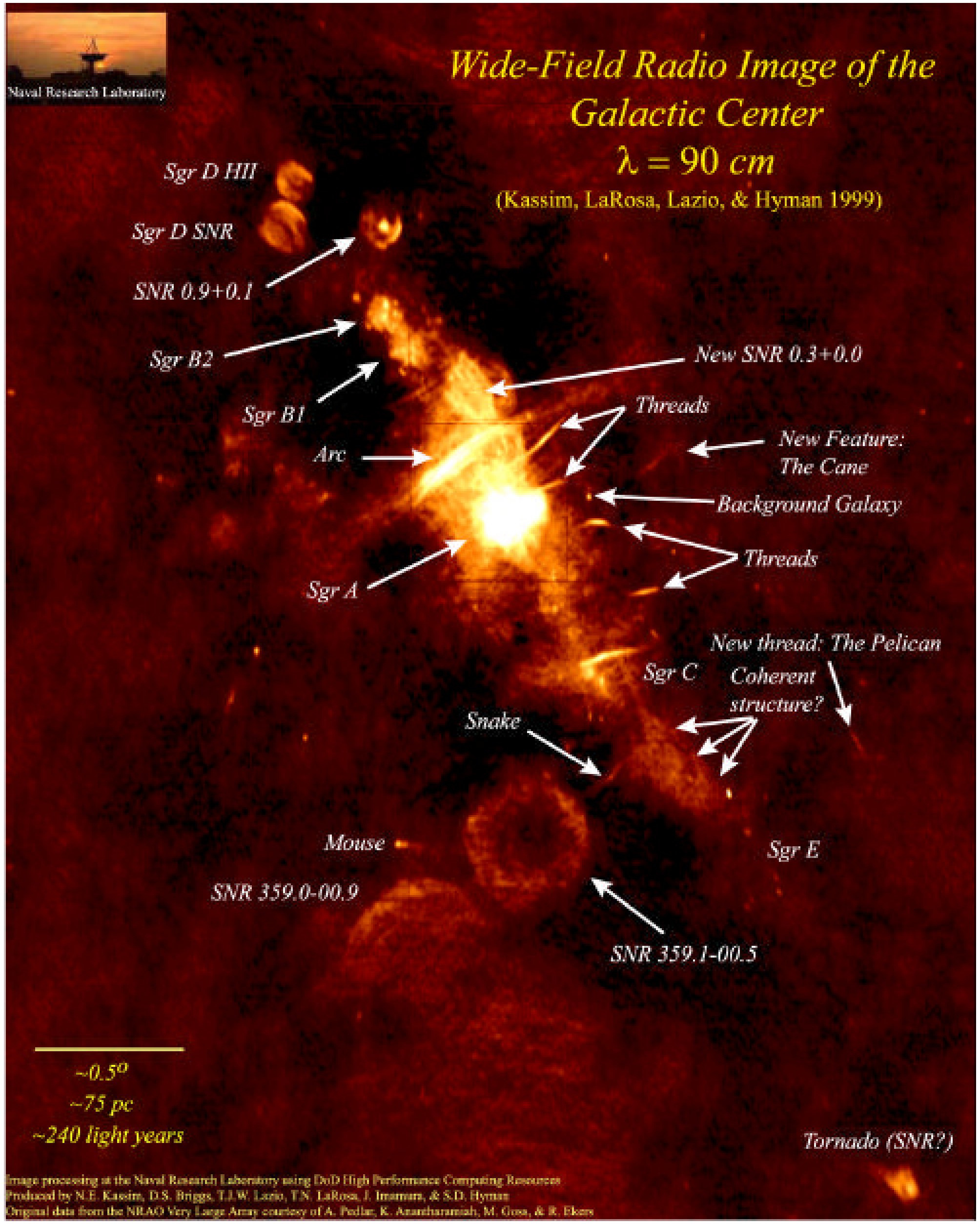
String of radio sources on either side, which may be H II regions.

Spectral line emission => rotational speeds 200 km/s at $r = 10^{16}$ m from center =>

$$M = \frac{rv^2}{G} = 3\times10^6 M_{Sun},$$

Implying a possible massive black hole within the central 1pc of our Galaxy.

The Galactic Center



Largest and most sensitive radio image of Galactic center at high-resolution.

A Scenario for Galaxy Evolution

- Spherical rotating cloud (size ~ 100 kpc) collapses, ~ 1.5 x 10^{10} yr ago
- First stars form during collapse => globular clusters, halo pop II stars
- Eventually a gas disk forms because of rotation and dissipation of internal KE of gas, ~ 10^{10} yr ago
- More star formation
- Density perturbation in disk => spiral structure
- New stars currently forming in spiral arms